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Introducing originality and innovation in engineering teaching: the hydraulic design of culverts

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Recently, the teaching of engineering design has become a presentation of standards and codes rather than the learning of sound design practices. Too many students request formulae and equations to solve a design exercise and they fail to develop any design originality. The present student attitude leads to young graduate engineers without critical ability and innovative flair. The writer has developed an innovative hydraulic design exercise based upon culvert design. Each design exercise could lead to more than one correct design per student in the class. Students have to learn basic design calculations based upon lecture material, notes, field visits and laboratory experiment. The practical component (laboratory, field visit) contributes significantly to their understanding of the complete system, including some basic safety and professional issues.

1. Introduction

The paper presents a new way to teach hydraulic design to civil and environmental engineering students in an undergraduate curriculum. The hydraulic design of a culvert is introduced as part of a complete design approach. The paper describes engineering design techniques in which individual originality and innovation is required. The analysis of the design procedures highlights the original input that each student must bring. Case studies are used to support the undergraduate teaching of open channel hydraulics and design of hydraulic structures. The standard text recommended in the course is *The hydraulics of Open Channel Flow: An Introduction* (Chanson 1999).

According to the dictionaries, an engineer is 'a designer or builder, a person who carries through an enterprise by skilful or artful contrivance' (e.g. *The Penguin English Dictionary* 1985–86, *Merriam-Webster's Collegiate Dictionary* 1997). In recent times, the teaching of engineering design has become more the presentation of standards and codes than the learning of design originality and safety. At undergraduate level and in postgraduate classes, too many students request formulae and equations to solve a design exercise. They fail often to read the specifications, to assess the problem and to analyse the tasks involved, and to develop an original design. The present student attitude leads to young graduate engineers without critical ability and innovative flair.

In practice, many engineers duplicate existing designs, including their mistakes. A famous example in hydraulic design is the spillway structure of the New Victoria dam, Perth (1990, Australia). The design of the spillway was copied from the Upper

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Stillwater dam (1987, USA). The US design was to be a 4.6-m long broad crest followed by a straight 59° stepped chute, but the final design is a 9.1-m long broad crest followed by a 72° chute and then a 59° chute. The change in design was made to allow truck access. It had no hydrodynamic or structural validity. In fact, the final design has increased the risks of jet deflection and improper operation during overflows at the transition between the crest and the 72° chute. None the less, the Upper Stillwater crest design was duplicated for the New Victoria dam spillway without critical analysis (Chanson 1997).

The author has developed an innovative hydraulic design exercise which could lead to more than one correct design per student in the class. Students must develop their individual expertise in culvert design. They have to learn how to calculate an efficient design based upon lecture material, notes, field visit(s) and laboratory experiment. They are expected to provide detailed drawings and justifications of their calculations.

1.1 *Culvert design*

A culvert is a covered channel of relatively short length designed to pass water through an embankment (e.g. highway, railroad, dam). The design requires a hydrological study of the upstream catchment to estimate the maximum (design) discharge and the risks of exceptional (emergency) floods. The dimensions of the culvert are based on hydraulic, structural and geotechnical considerations. Indeed, the culvert height and width affect the size and cost of the embankment. The culvert impact on the environment must also be taken into account, e.g. flooding of the upstream plain.

The design process is a system approach. The system must be identified as well as the design objectives and constraints. A detailed analysis of it must be conducted and the engineers should ask if their final design responds to the objectives.

2. Hydraulic design of culvert

The hydraulic performances of a culvert are the design discharge Q_{des}, the upstream total head and the maximum (acceptable) head loss ΔH. Head losses must be minimized to reduce upstream backwater effects (i.e. upstream flooding). The primary design constraints are: (1) the cost must be (always) *minimum*; (2) the afflux[1] must be small and preferably minimum; (3) eventually the embankment height may be given or may be part of the design; and (4) a scour protection may be considered, particularly if a hydraulic jump might take place near the culvert outlet. The hydraulic design is basically an optimum compromise between discharge capacity and head loss. In practice, short culverts are designed for free-surface flow with critical flow conditions[2] in the throat. The final design may vary from a simple geometry (i.e. standard box culvert) to a hydraulically-smooth shape (i.e. minimum energy loss (MEL) culvert[3]) (figures 1 and 2).

3. Standard culverts

A standard culvert is designed to pass water at *minimum cost.* The culvert construction must be simple, e.g. circular pipes, precast concrete boxes. The culvert flow may exhibit various flow patterns, e.g. free-surface inlet flow conditions or submerged entrance, inlet control or outlet control (figures 1 and 3).[4]

The discharge capacity of the barrel is primarily related to the flow pattern.

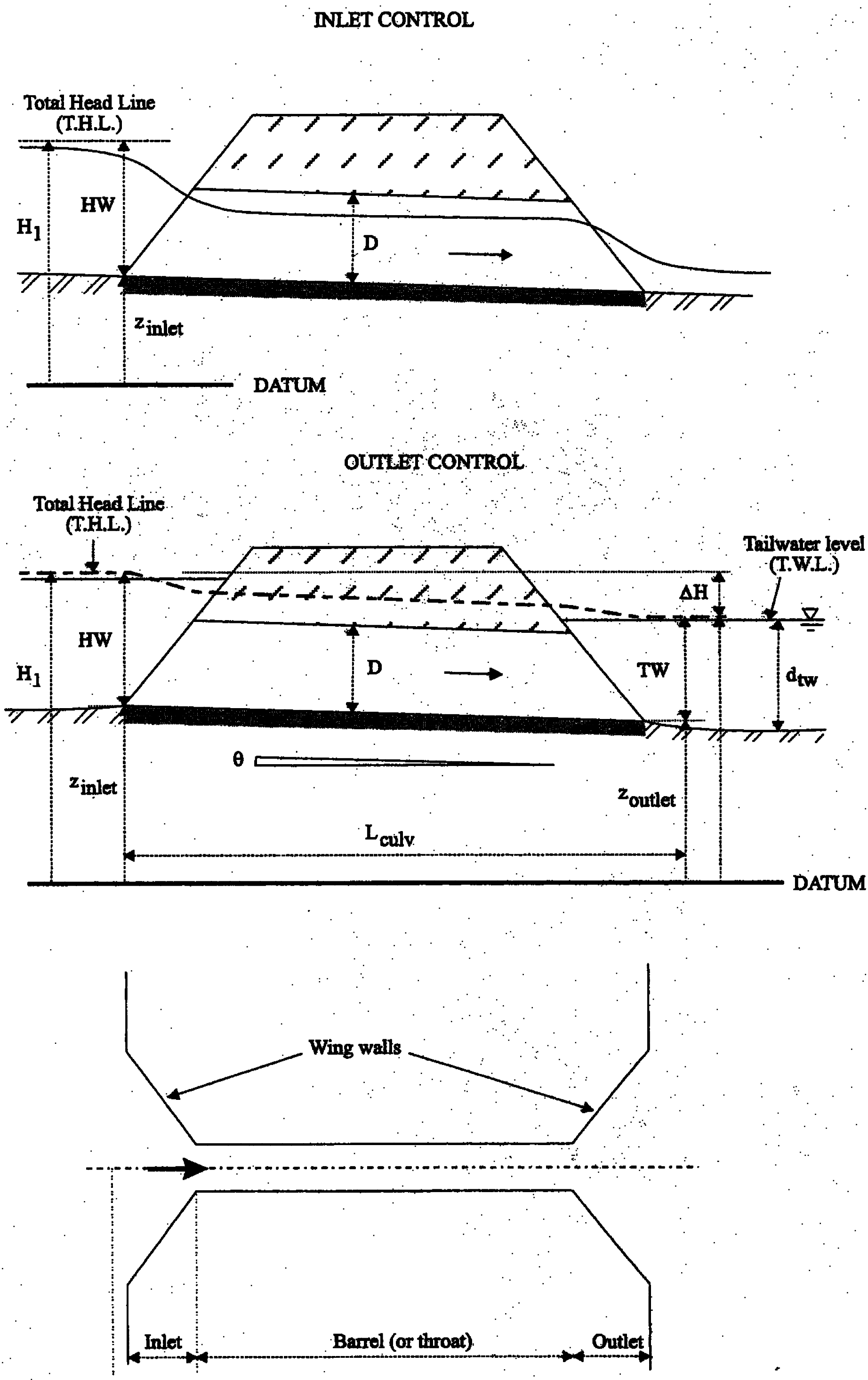


Figure 1. Sketch of a standard culvert operation: inlet control and outlet control.

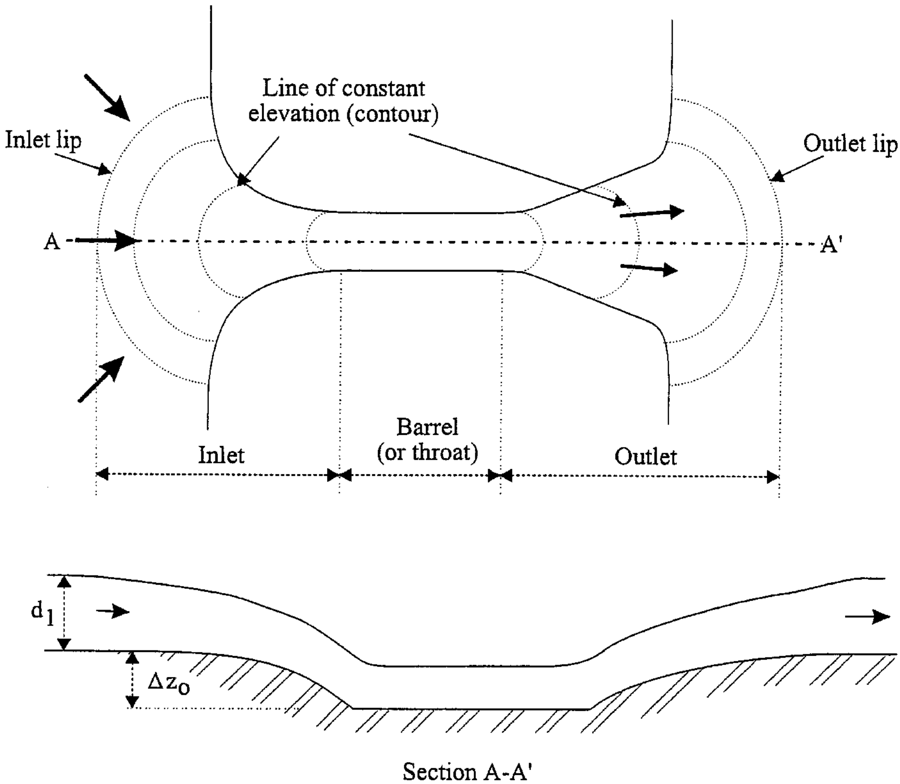


Figure 2. Sketch of a minimum energy loss culvert.

When free-surface flow takes place in the barrel, the discharge is fixed only by the entry conditions, and the discharge is typically estimated as:

$$\frac{Q}{B} = C_D * \frac{2}{3} * \sqrt{\left(\frac{2}{3} * g\right)} * (H_1 - z_{inlet})^{1.5} \qquad \text{Free-surface inlet flow (1)}$$

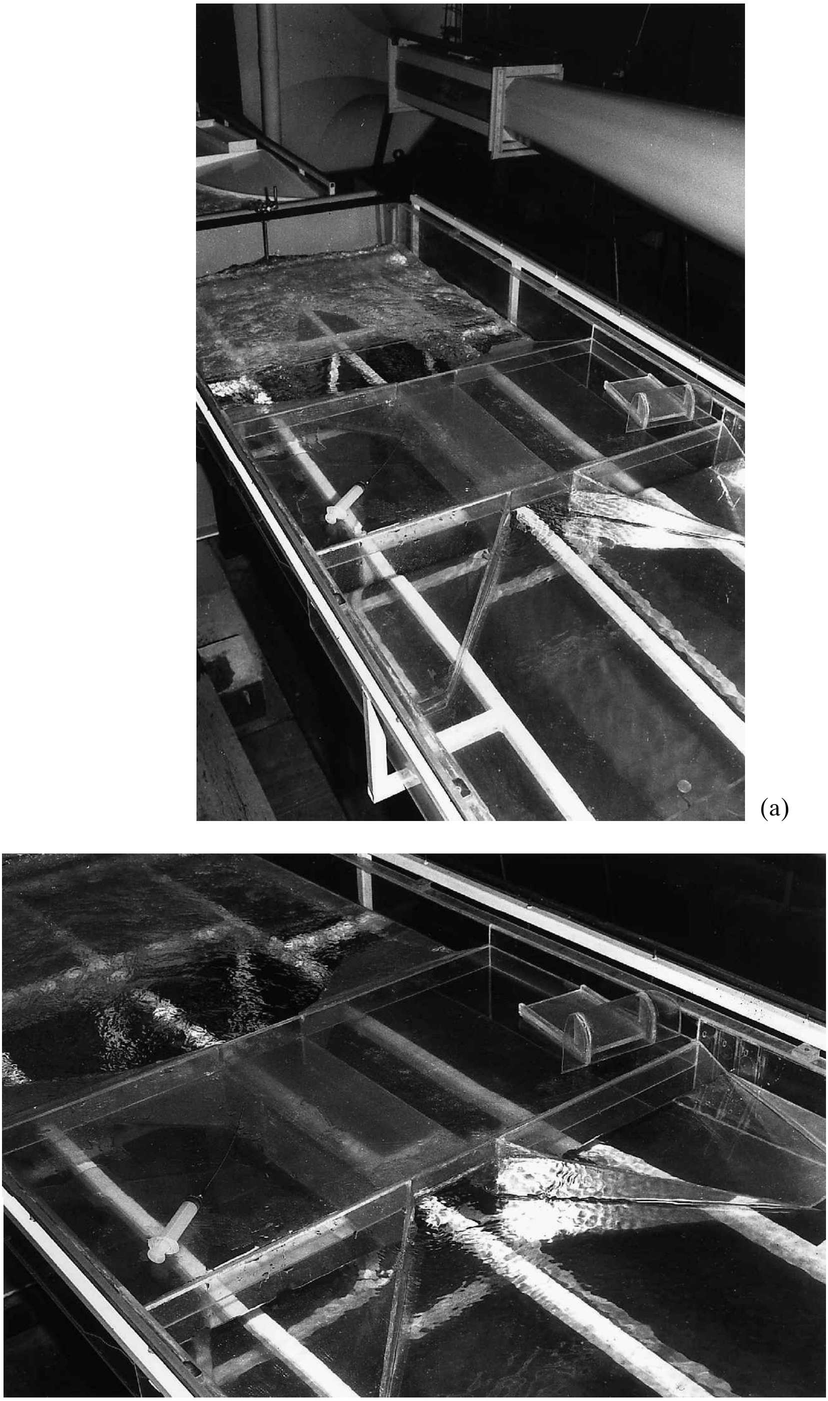
$$\frac{Q}{B} = C*D* \sqrt{[2*g*(H_1 - z_{inlet} - C*D)]}$$

Submerged entrance and free-surface barrel flow (2)

where B is the barrel width and D is the barrel height (figure 1) (Henderson 1966). C_D equals 1 for rounded vertical inlet edges and 0.9 for square-edged inlets. C equals 0.6 for square-edged soffit and 0.8 for rounded soffit. For drowned culverts (i.e. outlet control), the discharge is determined by the culvert resistance (i.e. primary and secondary losses) (e.g. US Bureau of Reclamation 1987, Concrete Pipe Association of Australasia 1991).

3.1. *Design procedure*

For standard culverts the design process is divided into two parts (e.g. Herr and Bossy 1965, HEC No. 5). First, a system analysis must be carried out to determine the objectives of the culvert, the design data, the constraints including the design flow Q_{des} and the design upstream total head H_{des}.



(a)

(b)

Figure 3. Examples of model box culvert operation. Design flow conditions: $Q_{des} = 10$ ls^{-1}, $d_{tw} = 0.038$ m, $S_o = 0.0035$, $B_{min} = 0.15$ m, $D = 0.107$ m, $L_{culv} = 0.5$ m. (a) Design flow conditions: view from upstream (flow from bottom right to top left): $Q = 10$ ls^{-1}, $d_{tw} = 0.038$ m, $d_1 = 0.122$ m. Note the hydraulic jump downstream of the culvert. (b) Non-design flow conditions: view from upstream of the drowned barrel (flow from bottom right to top left): $Q = 10$ ls^{-1}, $d_{tw} = 0.109$ m, $d_1 = 0.133$ m, outlet control.

In a second stage, the barrel size is selected by a test-and-trial procedure, in which both inlet control and outlet control calculations are performed. At the end, the *optimum size* is the smallest barrel size allowing for inlet control operation. Calculations of the barrel size are iterative:

(1) Choose the barrel dimensions.
(2) Assume an inlet control. Calculate the upstream total head corresponding to the design discharge Q_{des} assuming inlet control for different barrel sizes until the upstream head $H_1^{(ic)}$ satisfies the design specifications (i.e. $H_1^{(ic)} = H_{des}$).
(3) Assume an outlet control. Use design charts to calculate the head loss ΔH from inlet to outlet for the design discharge Q_{des} (e.g. US Bureau of Reclamation 1987). Calculate the upstream total head $H_1^{(oc)}$: $H_1^{(oc)} = H_{tw} + \Delta H$, where H_{tw} is the tailwater head at design flow.
(4) Compare the inlet control and outlet control results: $H_{des} = H_1^{(ic)} \gtrless H_1^{(oc)}$. *The larger value controls.*

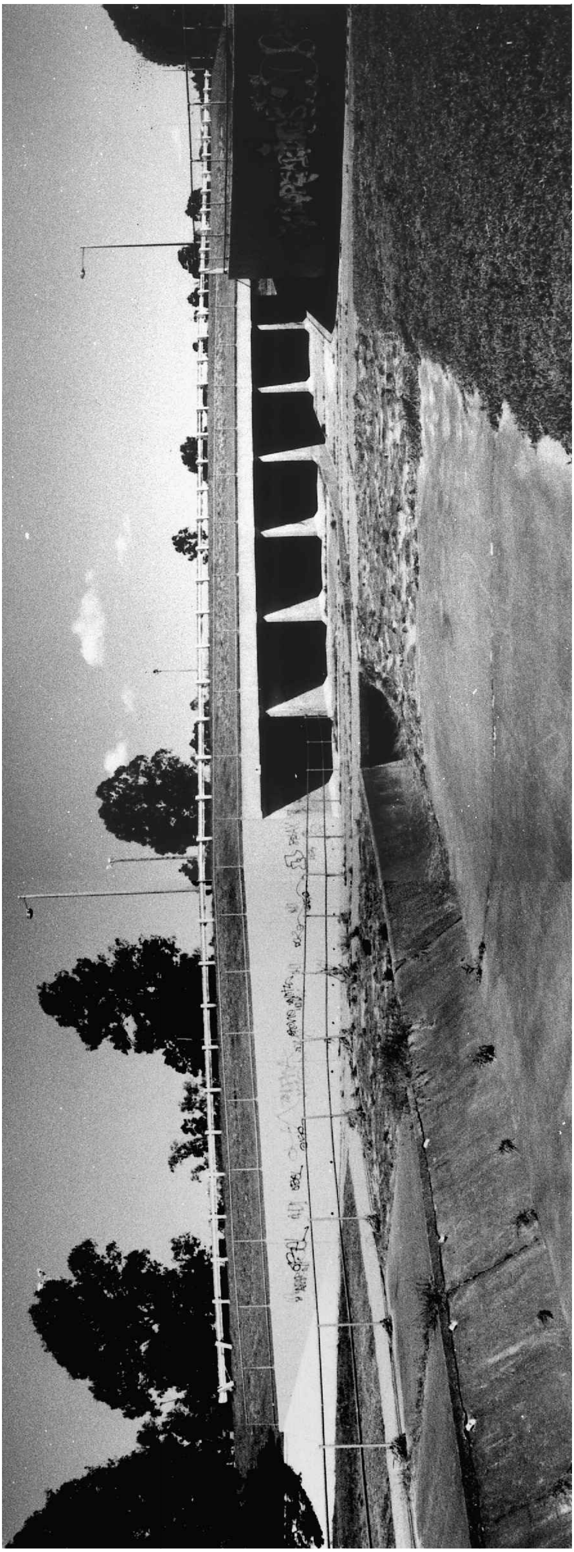
When the inlet control design head H_{des} (used in step 2) is larger than $H_1^{(oc)}$, inlet control operation is confirmed and the barrel size is correct. If $H_1^{(oc)}$ is larger than H_{des}, outlet control takes place. Step 3 must be then repeated with an increased barrel size until $H_1^{(oc)}$ satisfies the design specification H_{des}.

4. Minimum energy loss culverts

A MEL culvert is a streamlined structure designed with the concept of minimum head loss (figures 2 and 4). Apelt (1983) presented an anthoritative review of the topic. The basic design concepts are streamlining and critical flow conditions

(a)

Figure 4. Photographs of a prototype MEL culvert below Ridge Street, Brisbane, Queensland, Australia. Design discharge: 220 m^3s^{-1}; barrel: 7 cells (2-m-wide each). (a) View of the inlet: a bicycle path passes in one of the barrel cell. (b) View of the outlet. Note the low-flow channel in the foreground (left) and the bicycle path behind.



(b)

through all the waterway (inlet, barrel, outlet) (figure 5). The intake is designed with a smooth contraction into the barrel while the outlet (or diffuser) is shaped as a smooth expansion back to the natural channel. In a satisfactory design, the flow streamlines follow very smooth curves and no separation is observed as for a Venturmeter installed in a circular pipe. MEL structure are designed to achieve critical flow conditions in all the engineered waterway because the maximum discharge per unit width for a given specific energy is achieved at critical flow conditions (e.g. Henderson 1966). At the throat the discharge per unit width may be increased by lowering the barrel invert below the natural ground level.

4.1. *A simple design method*

Professor C. J. Apelt (The University of Queensland) proposed a simple method to calculate the basic characteristics of a MEL culvert. This method gives a preliminary design.[5] Full calculations using the backwater equations are required to predict accurately the free-surface profile.

1. Decide the design discharge Q_{des} and the associated total head line (THL) in the flood plain.

(A) Neglect energy losses

2.1. Calculate the waterway characteristics in the throat (i.e. barrel) for critical flow conditions.

2.2. Calculate the inlet width B_{max} assuming critical flow conditions and natural bed level (i.e. $\Delta z_o = 0$).

3.1. Decide the shapes of the fans.

3.2. Calculate the geometry of the fans to satisfy critical flow conditions everywhere (e.g. figure 7).
In the above steps, either the barrel width B_{min} is selected and the barrel invert drop Δz_o is calculated; or Δz_o is chosen and the barrel width is calculated.

(B) Include the energy losses

4. Adjust the bed profile of the waterway to take into account the energy losses.
5. Check the 'off-design' performances, i.e. $Q > Q_{des}$ and $Q < Q_{des}$.

5. Teaching culvert design

The author developed a pedagogic tool to introduce students to culvert design. It covers lecture material, home work associated with site visit(s) as well as a culvert laboratory study which includes an audiovisual presentation, physical models of culverts and numerical computations (using the program HydroCulv). The aim of the course is to introduce students to some original hydraulic design as well as to hydraulic computations of culvert design using a commercial package.

Following the lecture material, students are involved in home work associated with site visit(s) (individually or in groups). For a particular case study, the students are asked either to design a standard box culvert for a specified flow rate or to calculate the design discharge capacity of an existing structure, and the associated upstream water levels. Then they are requested to design a MEL waterway to pass a specific flood (e.g. 1 in 50 years flood) and to compare their design with the corresponding standard box culvert. For each site, there is usually a single optimum standard culvert design and a multitude of correct MEL design. The multiplicity of

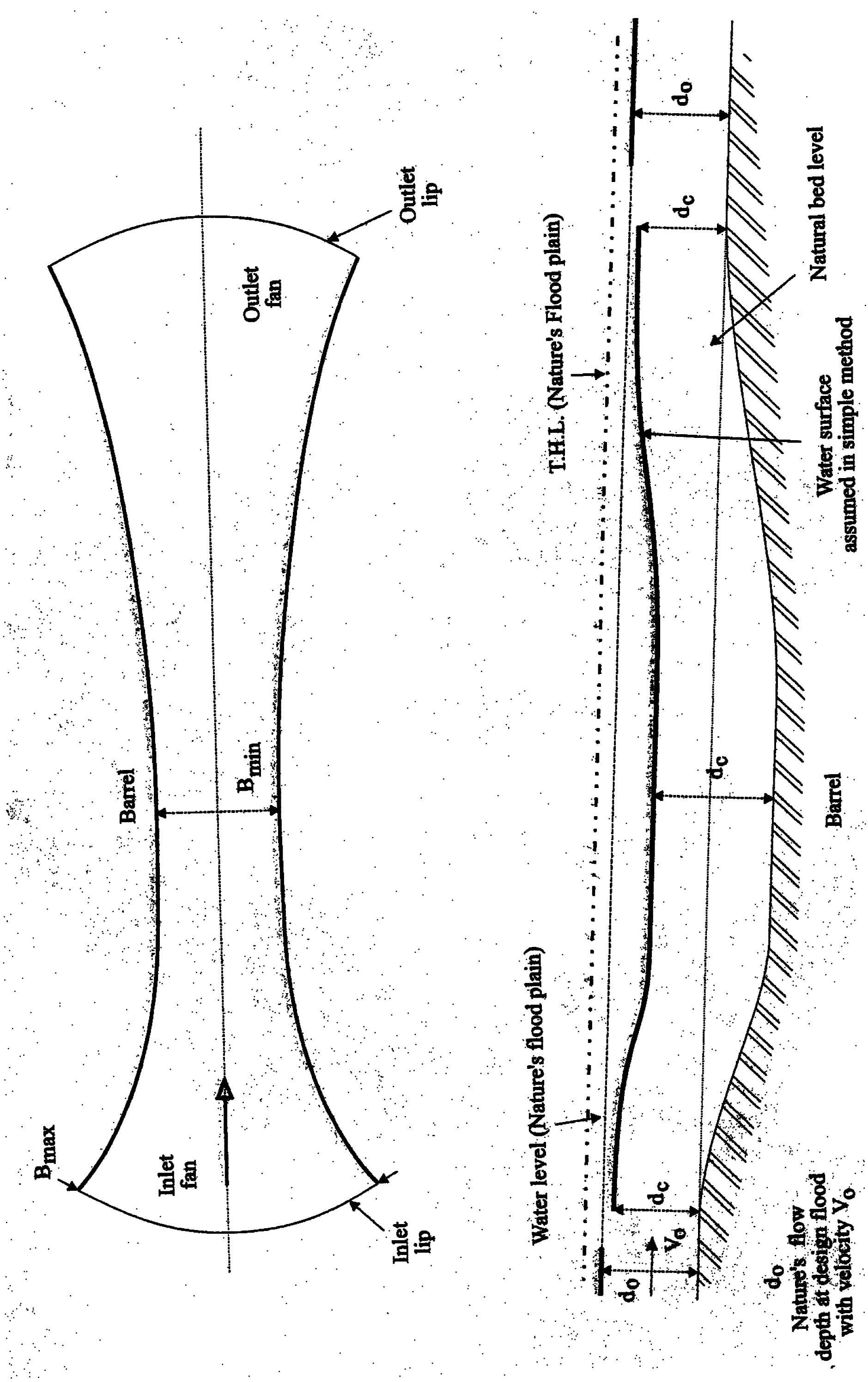


Figure 5. Free-surface profile assumed in the 'simple design method'.

MEL culvert designs results from the wide range of inlet and outlet shapes, e.g. parabolic, elliptic or hyperbolic sidewall curves.

Considering a practical application, the culvert design parameters are: design discharge = 100 m^3s^{-1}, barrel width = 8 m, zero afflux.[6] The students are asked to design a box culvert with zero afflux, a box culvert with an 8-m-wide barrel and a MEL culvert with zero afflux and an 8-m-wide throat. A standard box culvert with invert set at ground level would need to be 50-m-wide to pass the flood without afflux, while an 8-m-wide box culvert would cause an upstream water level rise (afflux) of about 4.4 m (figure 6). The MEL culvert design would require a 2.6-m deep excavation of the barrel. Figure 7 (a, b) shows proper inlet designs that would pass the design flow rate with zero afflux. Each figure shows the sidewalls and centre-line invert elevation only. Figure 7(c) presents an improper design that would create some upstream flooding for flow rates larger than 60% of the design flow rate.[7]

Note the significant differences between the standard and MEL culvert designs. The MEL waterway concept was developed by Profs G. R. McKay and C. J. Apelt for the coastal plains of Queensland (North-East of Australia). Torrential rains during the wet season, associated with very small natural plain flood slope ($S_o \sim 0.001$) and little fall (or head loss), place a heavy demand on culverts.

During each case study, the students may choose a multitude of inlet shapes. A correct design must be streamlined with occurrence of critical flow conditions at any location between the inlet lip and barrel. The complete inlet design requires the drawings of the lines of constant invert elevation. These are equipotential lines and the complete inlet design is similar to a flow net analysis (e.g. Vallentine 1969).

6. Laboratory work

Each student spends one afternoon in a hydraulic laboratory (see the appendix). The students are first introduced to culvert design (video presentation, Apelt 1994) before performing measurements in a standard box culvert model (figure 3) and a downstream MEL culvert model (figure 4). The models discharge an identical flow rate. They are made of fibreglass and perspex, and the students can see the flow patterns in the channel, barrel, inlet and outlet for design and non-design flow conditions[8] (figure 3). Identical flow conditions are input to a commercial software for standard culvert design (e.g. HydroCulv). Comparisons between the physical model and computer program results are conducted and discussed with the help of the physical model. The comparative performances of standard and MEL culverts are also discussed for design and non-design flow conditions. At the end of the afternoon, the students are challenged on the effect of a flood larger than the design flow. Their response is discussed in a group before being tested in the physical models for $1.5*Q_{des}$.

7. Discussion: a teacher's opinion

The author has taught hydraulic design at undergraduate and postgraduate levels for more than 10 years. At undergraduate levels, he introduces the students to spillway and culvert design. It is the author's opinion that the hydraulic design of a culvert offers a unique opportunity. The design exercise is based upon very basic hydraulic material, i.e. the concept of specific energy, critical flow conditions, ideal-fluid flow. Each case study may be developed as a series of design exercises with increasing complexity, e.g. starting with a standard culvert design and ending with a

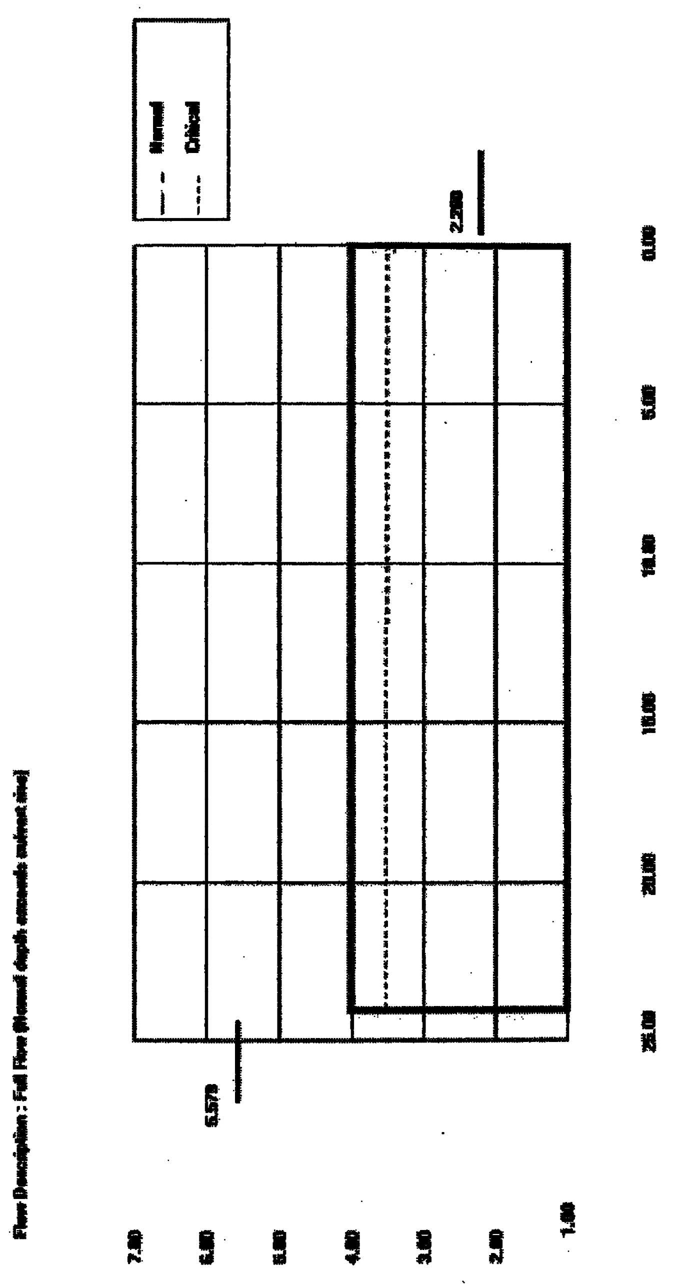
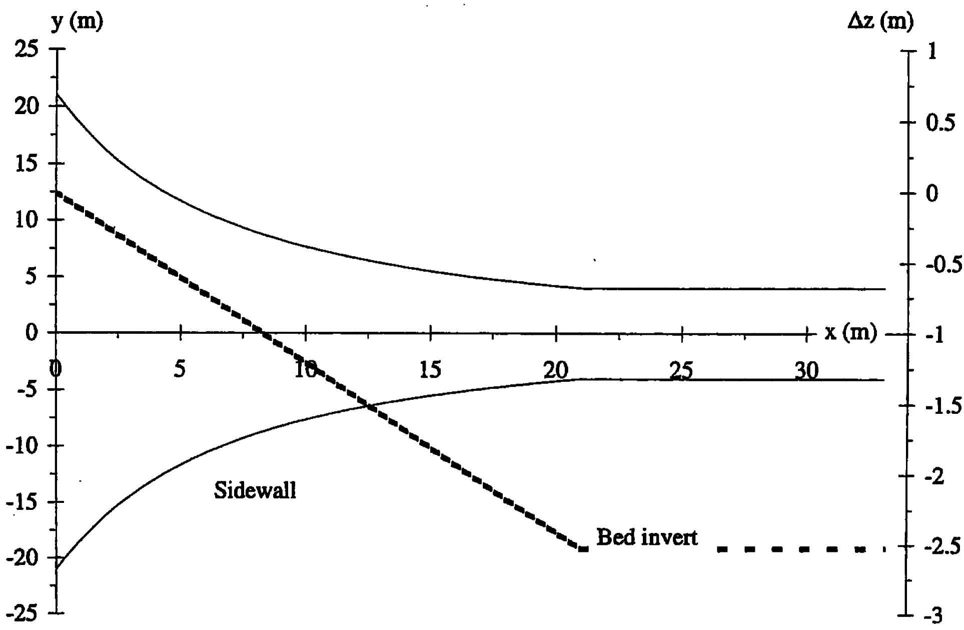
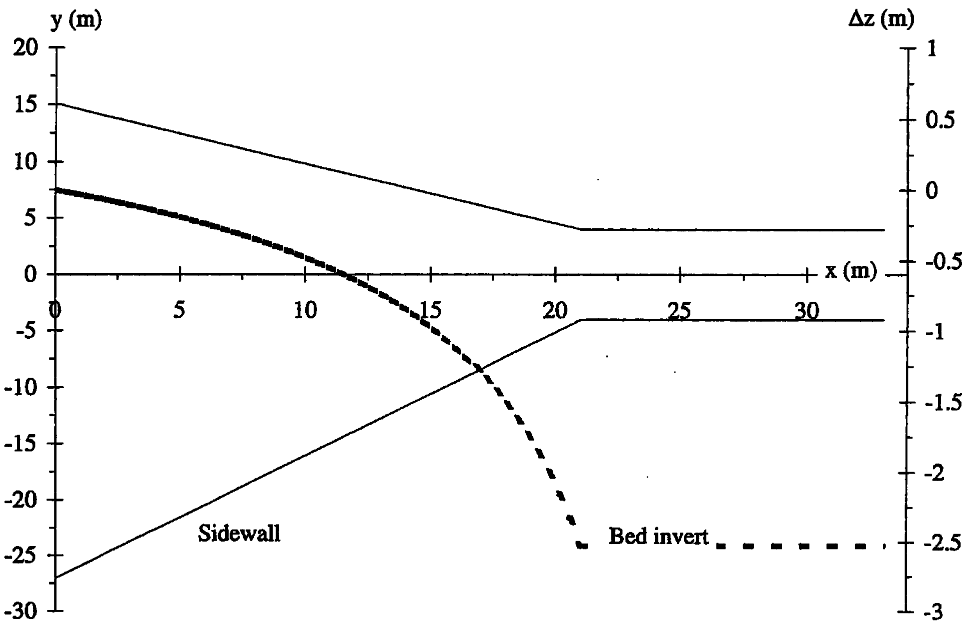


Figure 6. Free-surface computations for a standard box culvert (program HydroCulv). Design parameters: design flow rate = 100 m^3s^{-1}; barrel width: 8 m; normal depth in the flood plain (in absence of culvert): 1.2 m.

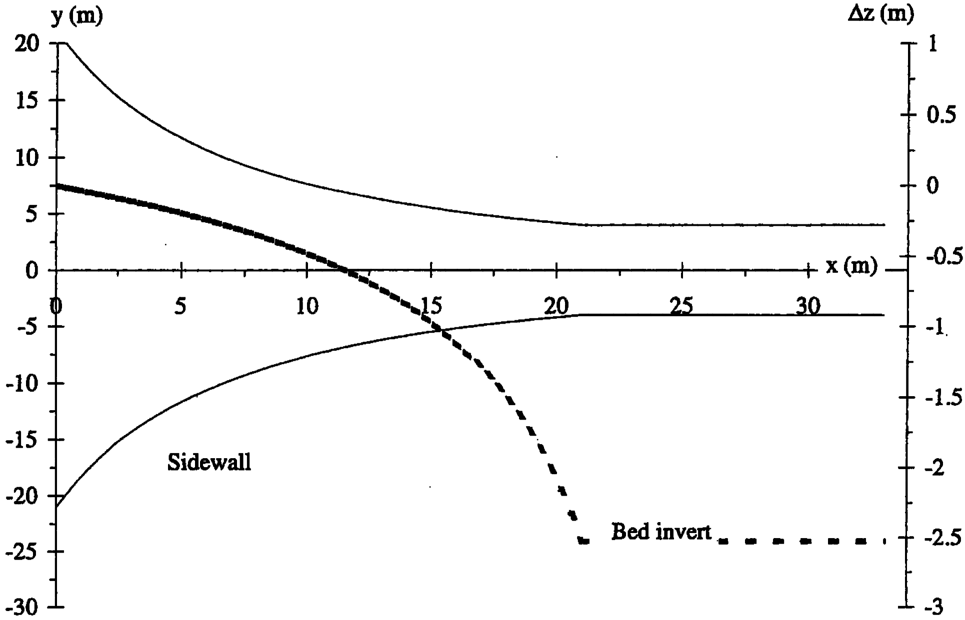


(a)



(b)

Figure 7. MEL culvert design. Design parameters: design flow rate = 100 m^3s^{-1}; barrel width: 8 m; zero afflux; normal depth in the flood plain (in absence of culvert): $d_o = 1.2$ m. (a) Correct design. (b) Correct design. (c) Improper design: upstream flooding will occur for $Q > 58\ m^3s^{-1}$.



(c)

MEL culvert design. Further, many case studies may be based upon prototype culverts. Standard culverts are very common and the students can inspect several sites. In Brisbane, there are, further, a number of MEL culverts that are easily accessible (e.g. figure 4).

The practical component of the teaching is very important, i.e. the field trip and laboratory experiment. The writer's experience suggests that students gain an optimum understanding when all teaching components are combined, i.e. lecture material, field visit, design exercise and laboratory experiment. The laboratory experiment is most useful to conduct comparisons between standard and MEL culvert performances, and also comparisons between physical modelling and computations.[9]

The field trips are often conducted with the lecturer and sometimes with professional engineers. The students learn of all the technical aspects of a culvert: road, embankment, boxes or pipes, drainage, etc. They can further picture the effects of upstream flooding. In the case of a MEL culvert, the students can appreciate the barrel and inlet design, the low-flow channel design. They are often surprised by the small excavation depth, not often perceptible.

By the end of the course, most students realize their ability to undertake the critical analysis of a professional design. They further understand that there might be more than one solution, and that the optimum design might be selected for non-technical reasons, e.g. politics when the Lord Mayor lives upstream of a new culvert!

Conclusion

The writer has developed an innovative hydraulic design exercise based upon culvert design. It aims to challenge the critical ability and innovative flair of the students, as indeed each design exercise may lead to more than one correct design per student in the class. Students have to learn basic design calculations based upon lecture material, notes, field visits and laboratory experiment. The practical component (laboratory, field visit) contributes significantly to their understanding of the complete system, including some basic safety and professional issues.

It is the author's opinion that the described teaching method has been very successful in the context of Australian civil and environmental engineering students. He further believes that the field visit under the supervision of the lecturer and sometimes of professional engineers gives an added dimension to the hydraullic design teaching.

Acknowledgements

The author thanks especially Prof. Colin J. Apelt, University of Queensland, for his help and assistance. The technical background of the paper derived from Prof. Apelt's personal lecture notes.

Appendix: Laboratory components

Audio-visual material:

Apelt, C. J., 1994, The minimum energy loss culvert, Video-cassette VHS colour, Department of Civil Engineering, University of Queensland, Australia, 18 min.

Physical model (standard culvert):

The physical model characteristics are: Q_{des} = 10 ls^{-1}, B_{max} = 1 m, B_{min} = 0.15 m, D = 0.11 m, L_{culv} = 0.5 m, d_{tw} = 0.038 m, intake and outlet: 45° diffuser, S_o = 0.0035.

Physical model (MEL culvert):

The physical model characteristics are: Q_{des} = 10 ls^{-1}, B_{max} = 1 m, B_{min} = 0.10 m, D = 0.17 m, barrel length: 0.6 m, d_{tw} = 0.038 m, barrel elevation 0.124 m lower than river bed.

Computer program:

HydroCulv Version 1.1 (HydroTools Software: dwilliams@compusmart.ab.ca).

Notes

1. The afflux is the rise of water level above normal free-surface level upstream of the culvert. It is a measure of the upstream flooding caused by the culvert design.
2. In open channel flows, the flow conditions, such as the specific energy is minimum, are called the critical flow conditions (e.g. Henderson 1966, Chanson 1999).
3. The design of a MEL culvert is associated with the concept of constant total head. The inlet and outlet must be steamlined in such a way that significant form losses are avoided. For an introduction on MEL culverts, see Apelt (1994). For a complete review of MEL waterways, see Apelt (1983).
4. Inlet control occurs when the flow is controlled by the upstream flow conditions and the flow rate is independent of the downstream water level.
5. The simple method is based on the assumption that the flow is critical from the inlet to outlet lips including in the barrel.
6. Other design parameters are: normal depth in the flood plain = 1.2 m (in absence of culvert), bed slope = 0.005, culvert length = 24 m. Barrel height = 3 m.
7. The extent of the upstream flooding could be determined with detailed backwater computations and physical modelling.
8. The experiments are conducted with flow rates ranging from 0.05 to 1.5 times the design discharge.
9. Most professional softwares perform one-dimensional or two-dimensional calculations. They fail to address the three-dimensional nature of the flow that may be visualized in the physical model.

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